

# Shallow Water Climatology and Analysis with Application to the Adriatic Sea

Craig M. Lee  
Applied Physics Laboratory, University of Washington  
1013 NE 40<sup>th</sup> St.  
Seattle, WA 98105-6698  
phone: (206) 685-7656 fax: (206) 543-6785 email: [craig@apl.washington.edu](mailto:craig@apl.washington.edu)

Grant #: N00014-02-1-0135  
<http://opd.apl.washington.edu/~craig/adriatic/>

## LONG-TERM GOALS

Long-range operational goals are to:

- Establish methods for characterizing a variety of littoral environments based on a combination of dynamics and archived measurements. Because this requires an extensible system capable of treating a range of coastal dynamics, considerable understanding of specific processes (e.g. freshwater plumes, upwelling zones, shelfbreak fronts, near-inertial waves) will be essential.
- Develop methods for assimilating remotely sensed and *in situ* measurements to produce three-dimensional estimates of instantaneous variability.

These contribute to our long-term scientific efforts to understand:

- The mesoscale dynamics of coastal environments (e.g. fronts, upwelling/downwelling, buoyancy plumes).
- Interactions between coastal and oceanic waters.
- Data assimilation techniques as applied to the study of three-dimensional dynamics.

## OBJECTIVES

This exploratory study will:

- Investigate new techniques for constructing climatologies in regions dominated by strong, episodic small- and meso-scale features, including compositing schemes based on dynamical regimes and retention of additional metrics for quantifying variability and errors.
- Extend the climatology with analysis products that employ remotely sensed and *in situ* measurements, climatological data and *a priori* assumptions regarding regional and temporal variations in the governing dynamics to produce estimates of instantaneous fields.
- Investigate how climatologies and analysis products might be used to optimize the deployment of limited in-situ sampling resources.
- Assemble archived data and develop a climatology for the Northern Adriatic Sea. This region will be used as a testbed for evaluating the techniques developed in the course of this study.

Report Documentation Page				Form Approved OMB No. 0704-0188	
Public reporting burden for the collection of information is estimated to average 1 hour per response, including the time for reviewing instructions, searching existing data sources, gathering and maintaining the data needed, and completing and reviewing the collection of information. Send comments regarding this burden estimate or any other aspect of this collection of information, including suggestions for reducing this burden, to Washington Headquarters Services, Directorate for Information Operations and Reports, 1215 Jefferson Davis Highway, Suite 1204, Arlington VA 22202-4302. Respondents should be aware that notwithstanding any other provision of law, no person shall be subject to a penalty for failing to comply with a collection of information if it does not display a currently valid OMB control number.					
1. REPORT DATE <b>30 SEP 2003</b>		2. REPORT TYPE		3. DATES COVERED <b>00-00-2003 to 00-00-2003</b>	
4. TITLE AND SUBTITLE <b>Shallow Water Climatology and Analysis with Application to the Adriatic Sea</b>				5a. CONTRACT NUMBER	
				5b. GRANT NUMBER	
				5c. PROGRAM ELEMENT NUMBER	
6. AUTHOR(S)				5d. PROJECT NUMBER	
				5e. TASK NUMBER	
				5f. WORK UNIT NUMBER	
7. PERFORMING ORGANIZATION NAME(S) AND ADDRESS(ES) <b>Applied Physics Laboratory, University of Washington,,1013 NE 40th St.,,Seattle,,WA, 98105</b>				8. PERFORMING ORGANIZATION REPORT NUMBER	
9. SPONSORING/MONITORING AGENCY NAME(S) AND ADDRESS(ES)				10. SPONSOR/MONITOR'S ACRONYM(S)	
				11. SPONSOR/MONITOR'S REPORT NUMBER(S)	
12. DISTRIBUTION/AVAILABILITY STATEMENT <b>Approved for public release; distribution unlimited</b>					
13. SUPPLEMENTARY NOTES					
14. ABSTRACT					
15. SUBJECT TERMS					
16. SECURITY CLASSIFICATION OF:			17. LIMITATION OF ABSTRACT <b>Same as Report (SAR)</b>	18. NUMBER OF PAGES <b>8</b>	19a. NAME OF RESPONSIBLE PERSON
a. REPORT <b>unclassified</b>	b. ABSTRACT <b>unclassified</b>	c. THIS PAGE <b>unclassified</b>			

## APPROACH

Improvements to the techniques used to quantify climatological fields in regions of strong variability represent a necessary first step towards improving the performance of nowcast/forecast efforts in shallow water environments. A simple extension will be the provision of metrics for expected variability about the climatological mean and for error estimates based on the underlying sampling. Although many climatologies provide seasonal (or sometimes monthly) estimates, informed selection of averaging intervals might produce more representative fields. Averaging periods will be chosen based on *a priori* knowledge of the dominant dynamics. This would separate periods dominated by upwelling and downwelling dynamics, or periods of high river run-off from those having low runoff. For example, in the wintertime Northern Adriatic we might form distinct estimates during Bora events and during periods of weaker atmospheric forcing, with the strength of the Po River runoff providing further differentiation. This differs from seasonal averaging because measurements from arbitrary times, but under specific dynamics, might form a single composite. The resulting mode-based climatology would be accessed by dynamic regime (and geographic location), rather than time.

Including additional *in situ* observations will probably always be the most effective way to improve nowcast/forecast accuracy. Thus, although we seek systems that minimize dependence on *in situ* measurements, part of this effort will examine techniques for assimilating *in situ* observations into the analysis. An extensive literature, including several textbooks, documents methods for mapping and assimilating observational data (see Robinson *et al.* 1998 for a review of applications in the coastal ocean). Most of these techniques rely on some combination of *a priori* statistical quantification of the variability and models of the relevant dynamics. The challenge will be to adapt methods that weight *in situ* measurements and climatological estimates in the context of prescribed dynamics while still being capable of real-time execution on modest computing resources.

A complementary avenue of investigation is the design of adaptive sampling strategies aimed at focusing a small number of *in situ* measurements towards locations that might yield the greatest improvements in nowcast accuracy. Results from Fox *et al.* (2001) suggest that the availability of a small number of critically located (e.g. eddy centers and edges) *in situ* profiles could have dramatically reduced the errors exhibited by the MODAS-produced sections. Much of the nowcast error lay in poor reproduction of the vertical structure associated with two eddies. The availability of a single vertical profile within each feature might have eliminated much of the error by forcing the model to incorporate the pycnostads associated with the eddies rather than simply using the nearly linear stratification specified by climatology. In the absence of remotely sensed fields, error and variance metrics developed for the new climatology formulations will be adapted to guide sampling. One approach would use covariance function estimates and data error variance derived from the climatology to produce error maps using standard objective analysis techniques. When remotely sensed fields are available, differences between the remotely sensed SST/SSH and climatological values could be weighted and included in these calculations. Ultimately, this study aims to produce a system that would prescribe the deployment of an arbitrary (but probably small) number of *in situ* observational resources. These measurements would then be used to constrain the predictions generated from remotely sensed surface measurements and climatological data.

## WORK COMPLETED

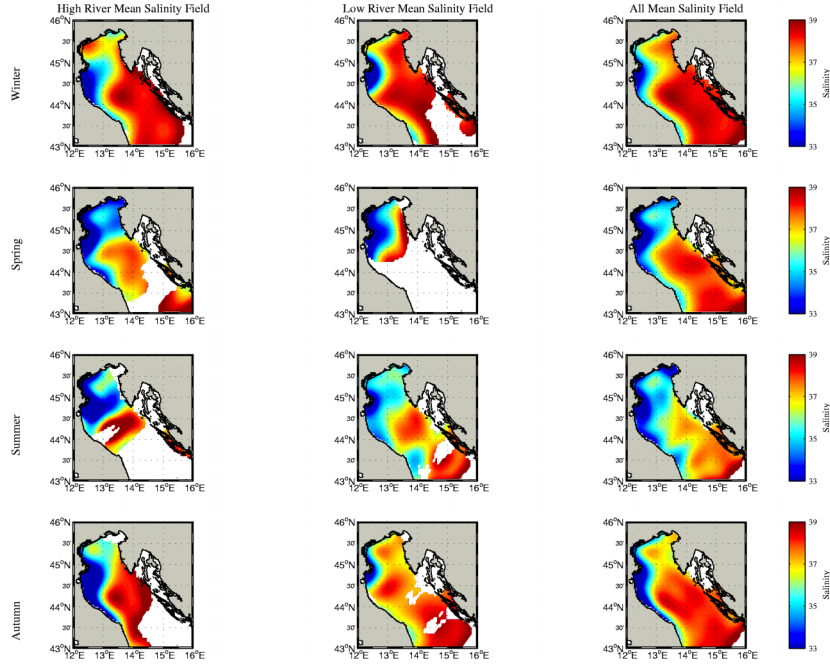
Efforts have focused on building scientific collaborations, compiling and organizing historical data and generating a new climatology of the Northern and Central Adriatic organized along the lines of the dominant forcing mechanisms. The Adriatic possesses an extended history of observations, with the literature pointing to numerous intensive field efforts undertaken by investigators from various nations. Marlene Jeffries, a University of Washington graduate student working on this project, has compiled archived hydrographic data from a wide range of sources, including the Mediterranean Online Database, the National Ocean Data Center, the OGS-Trieste archives and the data holdings of IPREM-Ancona. Access to Italian and Croatian archives has been generously granted as part of collaborative scientific efforts undertaken as part of our ongoing Adriatic Sea measurement program (ONR Grant #: N00014-02-1-0064). The resulting collection includes over 25,000 oceanographic profiles (CTD, XBT and bottle casts), Po River outflow measurements (monthly averages from 1918-1977, daily values from 1978-present) and hourly wind velocities at selected shore stations (1983-present). The profile data were used to estimate depth-dependant covariance functions for selected regimes of background stratification. Profiles were then organized according to Bora (strong northeasterly winds) and low-wind conditions, and by high and low Po River discharge. Objective analysis of the resulting ‘dynamically-organized’ subsets provides an alternative climatological characterization of the Northern and Central Adriatic. Current efforts focus on developing error metrics, further subdividing the dynamics-based classification scheme and incorporating synthetic (NRL-Monterey COAMPS model output) data to evaluate the technique.

In October 2002, a small group of coastal oceanographers and operational modelers met to identify promising new research directions for improving analysis product performance in nearshore environments. This meeting was organized in collaboration with Drs. Ruth Preller and Clark Rowley at the Naval Research Laboratory, Stennis Space Center. Participants summarized the present state of operational climatology/analysis products, reviewed the dynamics that govern variability in shallow water regimes and discussed directions for new research. The group issued specific recommendations for improving the availability and usage of archived data, enhancing the performance of climatologies and analysis/forecast products and developing new measurement capabilities. The ‘Shallow Water Analysis Methods Workshop Report’ summarizes workshop discussions and provides recommendations for future efforts.

## RESULTS

A climatology formed by exploiting *a priori* understanding of the dominant dynamics provides an alternative characterization of the Northern and Central Adriatic, capturing distinct features that are consistent with the basin’s observed response, but absent in conventional products. A combination of wind forcing (Bora and Sirocco), buoyant discharge (Po River, along with numerous smaller outflows) and seasonally variable background stratification governs the dynamics of the Northern and Central Adriatic. A climatological analysis keyed to Po discharge strength and seasonal stratification captures variations in Po plume morphology that are consistent with dynamically-based expectations (Fig. 1). During periods of weak stratification and low outflow, dynamics are weakly nonlinear and the plume is constrained to conserve potential vorticity. The plume turns right to follow isobaths as it enters the basin, remaining close to the Italian coast. At high discharge rates and weak stratification, advection balances vortex stretching and the plume can extend far into the basin. Under strong background stratification, the plume does not feel the bottom and readily spreads over much of the Northern basin.

In contrast, the fields created by seasonal averaging provide a less distinct characterization, with coastal confinement in autumn and winter, with broader spreading in spring and summer (Fig. 1).

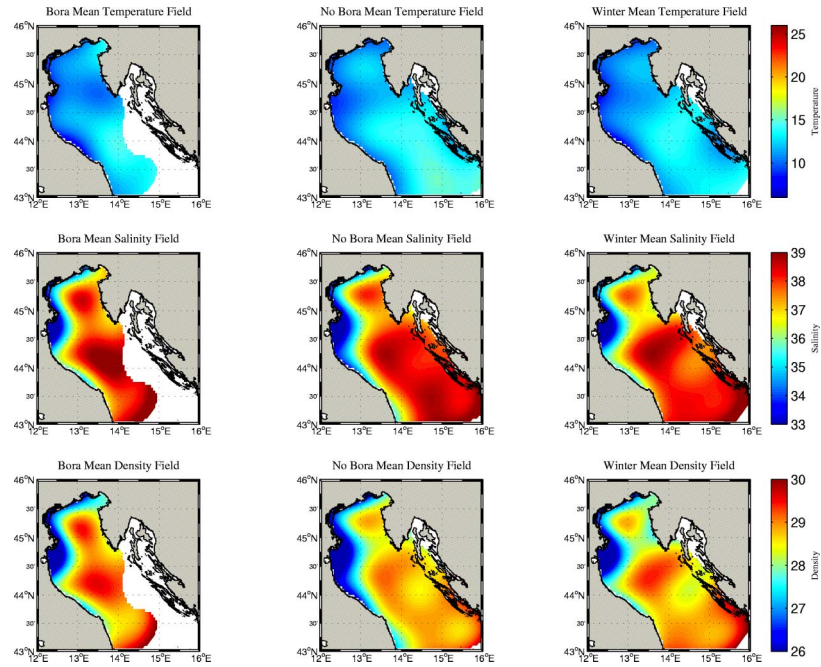


**Figure 1. Objectively analysed surface salinity maps for seasonal stratification regimes classified into (a) High Po River outflow, (b) Low Po River outflow and (c) All available data from the indicated season. Po plume salinity structure is consistent with dynamically-based expectations for low and high outflow regimes. The low- and high-outflow maps accentuate differences in Po plume position and extent relative to that depicted in the seasonal means (column 3). Wind variability was not accounted for in the analysis.**

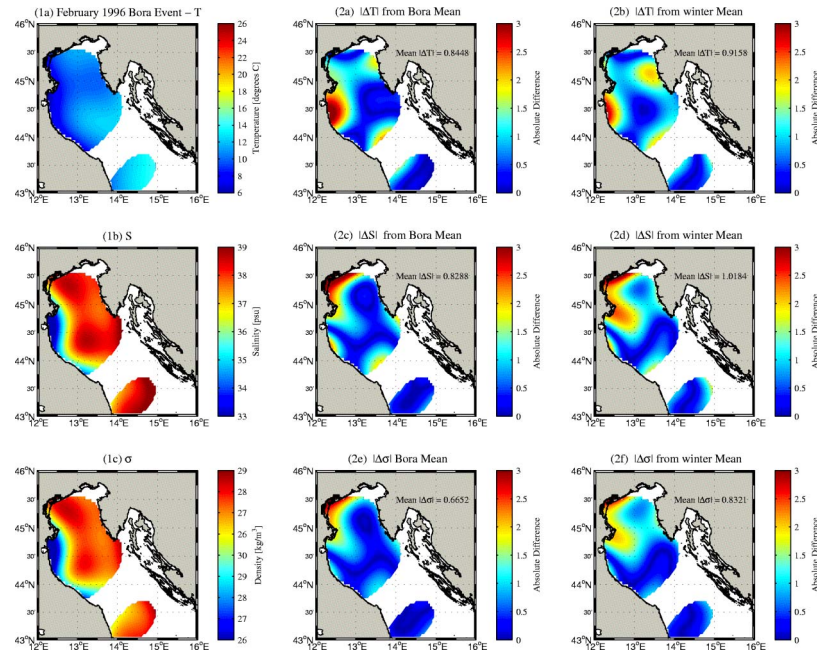
Bora cold air outbreaks offer another avenue for improving climatological characterization. During Bora, small-scale  $O(10 \text{ km})$  wind stress curl drives an alternating series of cyclonic and anti-cyclonic gyres which dominate the Northern Adriatic and entrain Po River water far into mid-basin (often reaching the Istrian coast). The associated latent heat loss drives full-depth convective overturning and the formation of North Adriatic Deep Water (NADW,  $\sigma_\theta > 29.2 \text{ kg/m}^3$ ). Small-scale variations in Bora winds govern the locations of dense water formation while Po river discharge modulates formation rate by providing a stabilizing freshwater cap. A climatology formed from Bora periods depicts two dense water pools (Gulf of Venice and south of the Istrian peninsula), both having top-to-bottom potential densities consistent with NADW formation (Fig. 2). The low-wind and winter-average fields also show dense pools (in slightly different locations), but in both cases potential densities are too low to be consistent with NADW formation. Comparing absolute differences (temperature, salinity and potential density) between a well-documented Bora event (February 1996) and both Bora and winter (seasonal) climatologies suggests that the Bora climatology offers a better characterization of the event (Fig. 3). The Bora climatology provides a better depiction of temperature, salinity and potential density variability in the Po-influenced region and within the dense water pools.

## IMPACT/APPLICATION

The Adriatic climatology demonstrates how informing climatological analysis with *a priori* knowledge of the dominant dynamics can enhance the resulting characterizations. The techniques used in this simple example could be introduced to other regions that possess distinct, characterizable dynamic regimes and sufficient archived data to enable the construction of climatological fields. The resulting climatology could offer a significantly improved ‘first guess’ for use in the absence of in situ data and as a starting point for data assimilation efforts.



**Figure 2. Wintertime climatology separated into Bora and non-bora regimes (columns 1 and 2) with the Winter mean for the same time period (column 3). Bora climatology depicts strong density gradients suggesting cyclonic flow around dense water pools. Although dense pools appear in all three maps, Bora climatology surface densities ( $>29.2 \text{ kg/m}^3$ ) are consistent with NADW formation by full-depth convection in the middle of the transient gyres.**



**Figure 3. Absolute differences between climatologies (Bora and seasonal/winter) and a documented Bora event (February 1996). Column 1 depicts objectively mapped surface  $T$ ,  $S$  and  $\sigma_\theta$  fields for the February 1996 Bora. Column 2 (3) indicates the absolute difference between the February 1996 event and Bora (seasonal/winter) climatological fields.**

## RELATED PROJECTS

Adriatic Circulation Experiment- Mesoscale Dynamics and Response to Strong Atmospheric Forcing, C. Lee (APL-UW).

Optical Dynamics in the Adriatic Sea: The Role of River Plumes, Filaments and Fronts in the Distribution, Advection and Transformation of Inherent and Apparent Optical Properties, B. Jones (USC).

Adriatic Mesoscale Experiment, P. Poulain (NPSG and OGS- Trieste).

East Adriatic Coastal Experiment (EACE), M. Orlic (Univ. of Zagreb).

Mesoscale Dynamics of the Adriatic Sea, B. Cushman-Roisin (Dartmouth).

The Adriatic Circulation Experiment, H. Perkins (NRL-Stennis), J. Miller (NRL- Stennis) and R. Signell (SACLANTCEN).

## REFERENCES

Fox, D. N., W. J. Teague, C. N. Baron, M. R. Carnes and C. M. Lee, 2001. The Modular Ocean Data Assimilation System (MODAS), submitted to the *Journal of Atmospheric and Oceanic Technology*.

Robinson, A. R., P. F. Lermusiaux and N. Q. Sloan , 1998. Data Assimilation. In *The Sea: The Global Coastal Ocean, Processes and Methods*, K. H. Brink and A. R. Robinson, eds. John Wiley and Sons Inc., New York, NY, 541-594.